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ATLANTA 26, GEORGIA

CALIBRATION PROCEDURES

FOR IDL AUTOMATIC OPTICAL PYROMETERS

by the Technical Staff

Instrument Development Laboratories Inc.

subsidiary of Kollmorgen Corporation

Attleboro, Massachusetts

MP MASTER
MA32731

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FOREWORD

One of the most common questions asked of IDL field engineers working on application of Pyro-Eye™ and Pyro-650™ automatic optical pyrometers is the basis of calibration. This is particularly true of instruments calibrated at higher temperature ranges.

It is the purpose of this paper to summarize the accepted international standards for definition of the temperature scale and the methods used by IDL to insure optimum calibration conformance of its pyrometers to this standard.

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by the

Technical Staff

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THE INTERNATIONAL TEMPERATURE SCALE

Introduction

The fundamental reference basis for calibration of any temperature measuring device is the International Temperature Scale as originally defined in 1927 by the Seventh General Conference of Weights and Measures. The original scale of 1927 has been revised in minor respects from time to time in the intervening years, the most important recent revision being that of 1948.

Basically, the International Temperature Scale consists of: (a) six primary fixed temperatures defined by equilibrium change-of-state temperatures of certain compounds or elements and (b) agreed methods of extrapolation between these fixed points and beyond the highest established fixed point.(1)

The Fixed Points

Fundamental fixed points and primary fixed points for the six reference temperatures are shown in Table I. The values for both the 1927 and the 1948 scales are given.

It is not believed necessary for routine technical purposes to describe the extensive work that has led to the determination of these values. It is worthy of note, however, to state that the establishment of the values for the scale points is based on a theoretically perfect gas thermometer.

Some idea of the accuracy with which these reference points are known may be of interest. The fundamental points, the melting point of ice and the boiling point of water at 1,013,250 dynes/cm^2 atmospheric pressure, are defined as exactly 0^o and 100^oC.

Table I. Fundamental Fixed Points and Primary Fixed Points Of The International Temperature Scale Under The Standard Pressure of 1,013,250 Dynes/cm^2

Fixed Point	Value Adopted	
	1927	1948
Temperature of equilibrium between liquid oxygen and its vapor (boiling point of oxygen)	-182.97°C	-182.970°C
Temperature of equilibrium between ice and air-saturated water (melting point of ice) (Fundamental fixed point)	0.000	0
Temperature of equilibrium between liquid water and its vapor (boiling point of water) (Fundamental fixed point)	100.000	100
Temperature of equilibrium between liquid sulfur and its vapor (boiling point of sulfur)	444.60	444.600
Temperature of equilibrium between solid and liquid silver (freezing point of silver)	960.5	960.8
Temperature of equilibrium between solid and liquid gold (freezing point of gold)	1063	1063.0

The accuracy of the sulfur point 444.600°C (1948) relative to the fundamental fixed points at 0°C is ± 0.1°C. By defining the point as exactly 444.600°C, however, and referring a platinum resistance thermometer to this control point, it is possible to reproduce this point for reference purposes with a precision of ± 0.005°C.

Similarly, the gold point 1063.0°C is based on two independent determinations of 1062.4°C[2] and 1064°C[3]. Thus the accuracy is approximately ± 1°C, but by referencing a platinum/platinum-rhodium thermocouple to a defined point of 1063.0°C, a reproducibility of about ± 1°C can be attained.

Interpolation between Points

For a continuous temperature scale, a practical and reproducible means is necessary for interpolation between the fixed reference points. The specific method varies with the range for which interpolation is desired.

In the region -182.97 to 630.5°C (1948 scale) the scale is defined by use of a standard platinum resistance thermometer, the purity and physical condition of the platinum being controlled by the specification that the ratio R_{100}/R_0 should not be less than 1.391 (1948).

For the purposes of interpolation, this region of the scale is subdivided into two parts: between 0° and 650.5°C a quadratic equation, $R_t = R_0(1+At+Bt^2)$, is used. This reduces to the familiar Callendar form,

$$t - t_{Pt} = \delta \cdot t(t-100)\,10^{-4}$$

in which t_{Pt} is defined as $100(R_t-R_0)/R_{100}-R_0)$. The constants of the equation are determined by measurements at the ice, steam, and sulfur points. It was, however, recommended in 1948 that the ice point should not be determined directly, but that it should be taken conventionally as 0.0100°C below the "triple point" of water, since it had been found that the triple point was more easily and accurately reproducible.

For temperatures below 0°C, the modified equation

$$R_t = R_0\left[1+At+Bt^2+C(t-100)\,t^3\right]$$

is used. This may be written in the Callendar-van Dusen form:

$$t - t_{Pt} = \delta \cdot t(t-100)\,10^{-4} + \beta t^3(t-100)\,10^{-6}$$

the additional constant being determined by measurement at the boiling point of liquid oxygen (-182.97°C). In 1927 the scale was extrapolated down to -190°C, but the extrapolation was found to be unreliable and the 1948 scale does not extend below the oxygen point.

For the range 630.5° to 1063°C (1948) the scale is defined by means of a 10% rhodium-platinum versus pure platinum thermocouple, using the quadratic equation $E = a + bt + ct^2$.

The constants are determined by measurements at the freezing points of antimony (630.5°C), silver, and gold. Since the antimony point is not one of the primary fixed points, and in order to ensure a measure of continuity with the resistance thermometer scale, it is laid down that the freezing point of the actual sample of antimony which is used shall be determined by means of the platinum resistance thermometer, and that the value so determined be used in the calculation of the thermocouple calibration. Alternatively, the thermocouple may be compared directly with the resistance thermometer at a temperature close to 630.5°C.

Extrapolation above 1063°C

Above 1063°C extrapolation of the scale is effected by means of a standard optical pyrometer, by means of which the luminous intensity of a blackbody at a given wavelength and at an unknown temperature above 1063°C may be compared with that of a blackbody at the freezing point of gold, a closely similar wavelength being used. In practice it is not possible to make the two wavelengths identical, owing to the difference between the spectral distributions of energy at the two temperatures, and a small correction has to be made for this change in effective wavelength. In the 1927 edition of the scale, extrapolation was made by means of Wien's law, from which we may derive the relative intensities at a given wavelength (λ) of two sources at different temperatures. If one of these is the gold point, then taken as 1336°K, we have:

$$\frac{J_T}{J_{Au}} = \frac{e^{\left[C_2/1336\lambda\right]}}{e^{\left[C_2/(t+273)\lambda\right]}}$$

The method of determining the ratio J_T/J_{Au} with a disappearing-filament optical pyrometer is to calibrate the pyrometer lamp on a blackbody at the freezing point of gold, and then to sight on the unknown higher temperature through a rotating sector disc of accurately measured transmission and computed to match the expected ratio as closely as possible. The exact ratio is determined from the lamp current after the unknown higher temperature has been adjusted to a match. With the ratio now established, we need to know the wavelength and the value of C_2 in order to determine the temperature.

The fundamental problem in application of Wien's law is the precise use of a narrow known wavelength λ and the accuracy with which the constant C_2 is known. In 1948 the best value of C_2 was 1.43848 ± 0.00034.[4] Some time later (1953) DeMond and Cohen further refined the figure to 1.43884 ± 0.00008.[5]

In the 1927 scale, extrapolation using Wien's law was limited to a value of about 4300°C for a normal wavelength of about 660mμ. By 1948 the need for extrapolation to higher temperatures led to a change to Planck's law for extrapolation beyond 1063°C:

$$\frac{J_T}{J_{Au}} = \frac{e^{[C_2/1336.15\lambda]}-1}{e^{[C_2/(t+273.15)\lambda]}-1}$$

where t = deg. Celsius.[11]

This relationship using Planck's law may be used for extrapolation indefinitely upward, and is the basic reference for calibration of all temperature measuring devices above 1063°C (1945°F).

Kelvin Scale

Reference is made frequently to the Kelvin scale. The definition of the Kelvin scale as of 1948 is a thermodynamic absolute scale having only a single fixed point, provided at present by the triple point of pure water, of which the absolute temperature is fixed at 273.16°K. The introduction of this new scale in no way affects the use of the International Scale, which remains the recommended practical scale and is expressed in °C (Celsuis). The triple point of water is 0.0100°C; so for engineering purposes the old simple relation °C + 273 = °K is valid within about 0.15°C. (0°C = 273.15°K)

Summary

The material presented here summarizes the International Temperature Scale as defined for fundamental use. In optical pyrometry we are primarily concerned with temperatures involving extrapolation above the 1063°C gold point. It is interesting to note that the temperature scale in this region is defined by a mathematical relationship (Planck's law) of energy measurement by optical pyrometry means. Thus, with a properly designed optical pyrometer, the instrument may be calibrated theoretically without physical reference standards other than at one point on the scale. In actuality, calibration against precalibrated working standards is more convenient for practical pyrometry over the range where such standards are available. This normally is up to about 2200°C. For higher temperatures, the mathematical relations of Planck's equation may be used by procedures to be outlined herein.

Precalibrated "working" standards do exist at approximately 2800°C (zirconium arc) and 3800°C (carbon arc) but are not stable reference sources for precise calibration checks.

THE INTERNATIONAL TEMPERATURE SCALE AS USED FOR IDL PYROMETERS

The basic international scale used for calibration of IDL pyrometers is the International Temperature Scale of 1948. The value of C_2 used in Planck's equation is 1.4385×10^7 (the 1948 value). [12]

IDL brightness pyrometers use a nominal effective wavelength of 653 $m\mu$, and the scale is computed on that basis. As can be seen from the preceding section, the exact choice of 650, 653, 660, etc. is immaterial as long as the wavelength is known and the scale so computed. Instruments properly calibrated for their own effective wavelength will theoretically agree in indicated temperature if the wavelength is known and radiation in the wavelength region has blackbody characteristics.

For extrapolation of the Pyro-650 brightness scales, the energy ratios relative to the gold point are shown for typical temperatures in Table II.

Table II. Energy Ratios to Gold Point (1063.0°C)

(Planck's Equation: $C_2 = 1.4385 \times 10^7$, $\lambda = 653\ m\mu$)

T °C	J_T/J_{Au}	T °C	J_T/J_{Au}
1063	1.000	2800	11,168
1100	1.558	2910	14,300*
1200	9.629	3000	17,314
1300	11.981	3200	25,508
1400	27.669	3400	36,046
1435	31.22*	3500	42,208
1500	58.141	3600	49,188
1600	112.88	3800	65,148
1680	182.91*	4000	84,114
1700	204.86	4200	105.896
1800	351.18	4400	131,005
1900	572.69	4600	159,199
2000	894.56	4800	190,825
2200	1,960.	5000	225,377
2230	2,180. *	5200	263,295
2400	3,817.	5400	304,309
2500	5,140.	5600	348,650
2600	6,778.	5800	395,518
2700	8,770.	6000	445,277

* Points indicated are specific points used in illustrative calibration computations in this text.

PYRO-650 CALIBRATION PROCEDURES TO 2300°C

The Tertiary Pyrometer Method

For calibration of Pyro-650 brightness pyrometers from the lower limit of 800°C to about 2300°C, the working reference standard is a heavy strip filament, General Electric pyrometer lamp used in conjunction with a Leeds & Northrup manual optical pyrometer calibrated and certified by the National Bureau of Standards. Copy of a typical certificate is shown in Table III.[6]

Table III.

UNITED STATES DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
WASHINGTON 25, D. C.

National Bureau of Standards

Certificate

OPTICAL PYROMETER
(L&N #1559289, Lamp YD-46)

Submitted by

Instrument Development Laboratories, Incorporated
67 Mechanic Street
Attleboro, Massachusetts

Corresponding Values of Scale Reading and Temperature when Sighting on a Blackbody

L Range		H Range		XH Range	
Scale Reading	Degrees C (Int. 1948)	Scale Reading	Degrees C (Int. 1948)	Scale Reading	Degrees C (Int. 1948)
800	800	1100	1098	1500	1503
850	847	1200	1195	1600	1599
900	896	1300	1294	1700	1698
950	945	1350	1344	1800	1797
1000	995	1400	1395	1900	1897
1025	1020	1450	1446	2000	1998
1050	1046	1500	1497	2100	2100
1100	1097	1550	1548	2200	2202
1125	1123	1600	1600	2300	2304
1150	1148	1650	1651	2400	2408
1200	1200	1700	1702	2600	2617
1225	1226	1750	1754	2800	2826

The values in the above table apply when the portion of the lamp filament below the wire marker is matched in brightness with the object sighted upon. The maximum uncertainties in the temperature values reported decrease from about ±4 degrees at 800°C to about ±3 degrees at 1063°C and then increase to about ±8 degrees at 2800°C. Accuracy of this order can be realized in practice only by keeping all the optical parts clean and checking the lamp calibration regularly to ascertain that significant changes in the characteristics of the lamp have not occurred.

For the Director

Henry J. Kostkowski

Henry J. Kostkowski
High Temperature Measurements Laboratory
Heat Division

P. O. No. C36012
Test No. 162277
Completed: July 27, 1960
EL/mr

Table IV. Apparent Blackbody Color Temperature versus Brightness Temperature for Tungsten Filament Lamps*

(T_T) Blackbody True Temp.	(T_B) Brightness Temp.	(T_C) Color Temp.	(T_T) Blackbody True Temp.	(T_B) Brightness Temp.	(T_C) Color Temp.
760	722	767	1760	1609	1793
780	741	788	1780	1627	1814
800	759	808	1800	1644	1835
820	778	828	1820	1661	1856
840	796	849	1840	1678	1877
860	814	869	1860	1694	1898
880	833	889	1880	1710	1919
900	851	909	1900	1726	1940
920	870	930	1920	1742	1961
940	888	950	1940	1759	1982
960	906	971	1960	1776	2002
980	924	991	1980	1793	2023
1000	942	1011	2000	1809	2044
1020	961	1032	2020	1826	2965
1040	979	1052	2040	1843	2086
1060	997	1073	2060	1859	2107
1080	1015	1093	2080	1875	2128
1100	1033	1113	2100	1892	2149
1120	1051	1134	2120	1908	2171
1140	1069	1154	2140	1925	2192
1160	1088	1175	2160	1941	2213
1180	1107	1195	2180	1958	2234
1200	1126	1215	2200	1975	2255
1220	1145	1236	2220	1991	2276
1240	1163	1256	2240	2008	2297
1260	1179	1277	2260	2024	2318
1280	1195	1298	2280	2040	2339
1300	1212	1318	2300	2056	2360
1320	1228	1339	2320	2072	2382
1340	1246	1359	2340	2088	2403
1360	1263	1380	2360	2104	2424
1380	1281	1401	2380	2120	2446
1400	1299	1421	2400	2136	2467
1420	1317	1442	2420	2152	2489
1440	1334	1462	2440	2168	2510
1460	1352	1483	2460	2184	2531
1480	1370	1504	2480	2200	2553
1500	1387	1524	2500	2216	2574
1520	1405	1545	2520	2232	2596
1540	1422	1565	2540	2248	2617
1560	1439	1586	2560	2264	2639
1580	1457	1607	2580	2279	2660
1600	1474	1627	2600	2295	2682
1620	1491	1648	2620	2311	2703
1640	1508	1669	2640	2326	2725
1660	1525	1689	2660	2342	2747
1680	1542	1710	2680	2358	2768
1700	1558	1731	2700	2374	2790
1720	1575	1752			
1740	1592	1773			

* The data for this Table was obtained from the Handbook of Chemistry & Physics, 38th Ed., p. 2720.

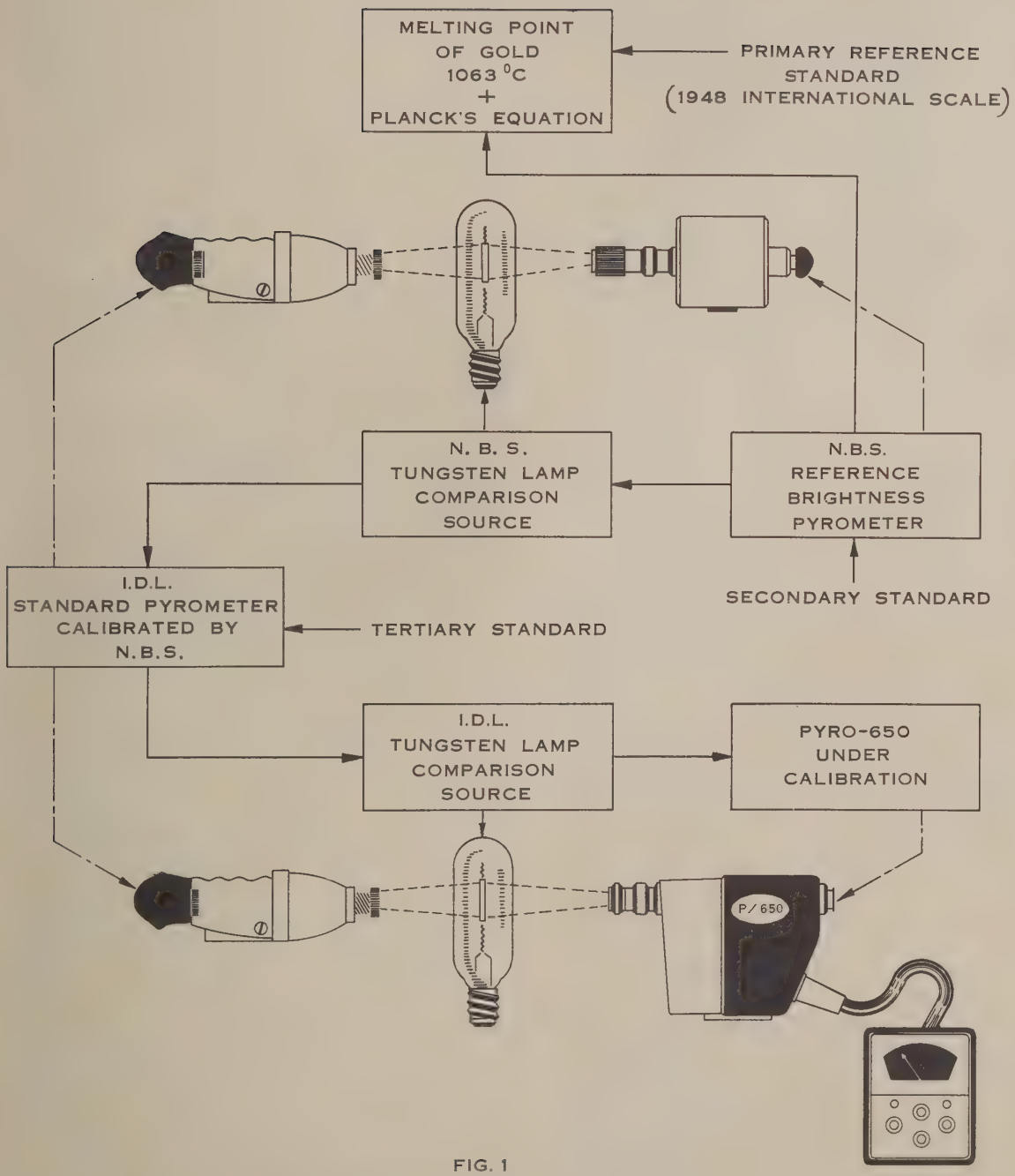


FIG. 1
PYRO-650 CALIBRATION SCHEMATIC

Functionally, the NBS calibrated manual pyrometer is used to determine the temperature of the tungsten lamp filament (Fig. 1); the filament is then measured by Pyro-650 for calibration reference purposes. Although tungsten sources are used both by NBS and IDL as comparison references, the calibration of the reference standard pyrometer at NBS is in terms of blackbody sources, so all comparison calibration is automatically in terms of a blackbody source, even though tungsten has an emissivity lower than unity. The tungsten filament itself is at a higher actual temperature than the pyrometers read.

In earlier sections the accuracy and reproducibility of the International Temperature Scale were discussed and noted to involve quite small errors when points were reproduced by basic international laboratory techniques. For practical instrument work, it is not feasible to realize such accuracy and reproducibility, as routine calibration must be made from tertiary standards and without benefit of the involved statistical procedures used in fundamental scale determinations. (Routine IDL calibration does require a minimum of three readings each by two operators at critical temperatures on each scale.)

There are three sources of calibration error involved in practical calibration:

1. The uncertainties of the secondary NBS standard at the National Bureau of Standards.
2. Uncertainty in the tertiary standard calibrated by NBS with reference to the secondary standard.
3. The additional uncertainty introduced by the calibration procedures for each production instrument relative to the secondary standard.

Maximum over-all uncertainties in the corrected readings of the tertiary standard pyrometer, with proper care and rechecking of the lamp in the tertiary standard, are quoted by NBS as follows:

at 800°C ± 4°C

at 1063°C ± 3°C

at 2800°C ± 8°C

This uncertainty of the tertiary standard is plotted in Fig. 2.

Up to slightly over 2300°C the strip filament pyrometer lamp used in Pyro-650 calibration is sufficiently stable on a short-term basis to be used as a stable intermediate reference source, the temperature of which is determined by the NBS tertiary standard pyrometer each time a calibration reading is made. This places a requirement, on the lamp only, that the supply circuit insure stable but adjustable voltage to the lamp. If the lamp voltage were used for long-term calibration reference, the accuracy of voltage (or current) measurement would be critical, and lamp calibration stability with life would limit routine use of the lamp to about 2200°C.

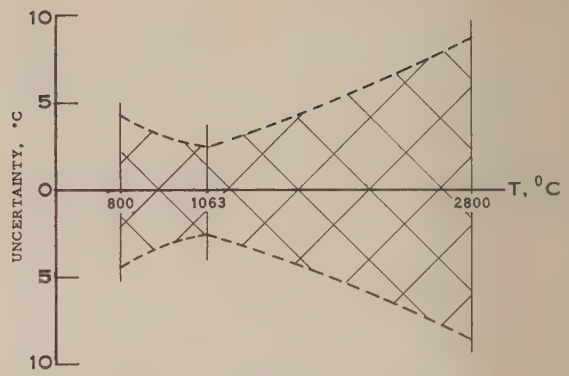


FIG. 2
UNCERTAINTY IN NBS CALIBRATION OF TERTIARY WORKING STANDARD

Errors introduced in calibrating a Pyro-650 by the method of Fig. 1 come from several sources: (1) operator ability to match the image in the tertiary standard; (2) operator ability to null and read the tertiary standard; (3) operator ability to read the Pyro-650 under calibration.

The magnitude of uncertainty due to the calibration procedure of Fig. 1 is estimated in Fig. 3.

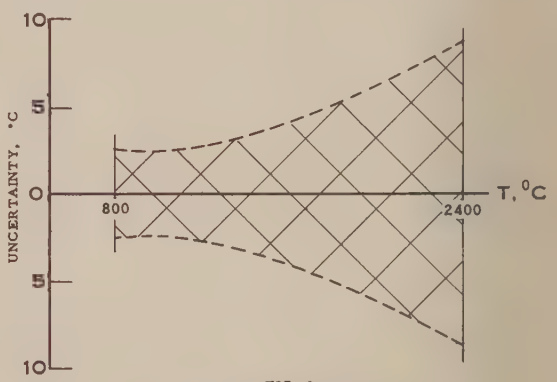


FIG. 3
UNCERTAINTY IN CALIBRATION COMPARISON OF PYRO 650 AND TERTIARY WORKING STANDARD

Over-all Pyro-650 uncertainty will be the proper summation of uncertainties of the NBS calibration of the tertiary or working standard (Fig. 2) and calibration procedure uncertainties (Fig. 3). If the meter scale is read directly, without reference to the calibration curve, meter scale uncertainties must also be added. These depend on the actual scale in use.

To facilitate routine calibration procedures, IDL can supply a convenient Pyrometer Calibrator (Fig. 4).

The Standardized Lamp Method

An alternate method of calibration for pyrometers is currently in process of development (Aug. 1961) at IDL and will be used if it demonstrates expected improvements in residual errors over the tertiary

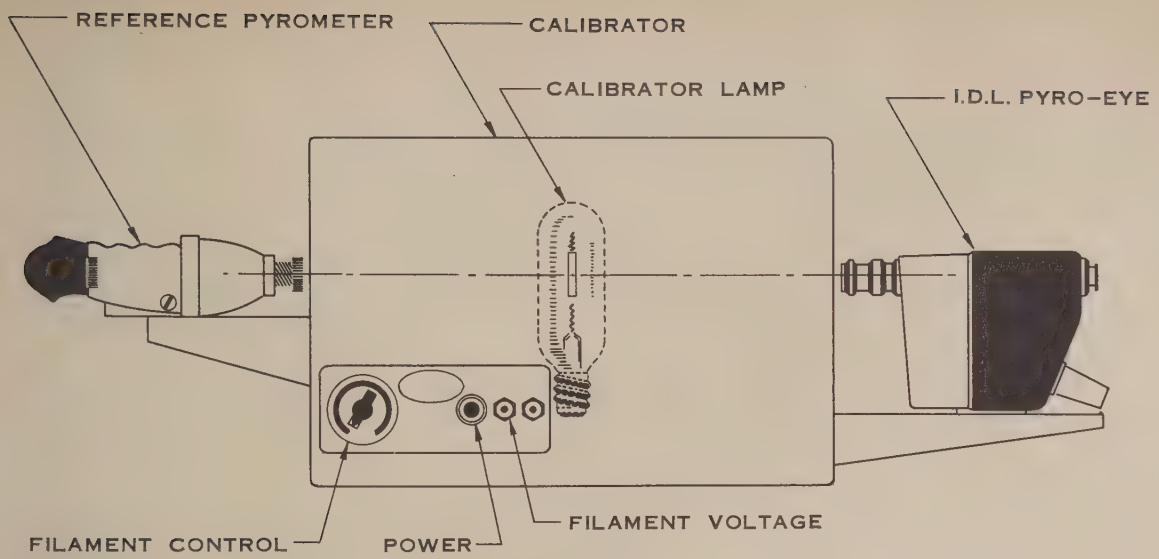


FIG. 4
I.D.L. PYROMETER CALIBRATOR

standard pyrometer method. The method is not unique, being patterned on techniques developed by other laboratories such as AVCO, Burlington, Mass.

Basically, the standardized lamp method uses a heavy filament pyrometer reference lamp such as that employed in the IDL pyrometer calibrator, but the lamp has been aged and calibrated by the National Bureau of Standards in terms of brightness temperature versus lamp current. By precise control and measurement of lamp current, the temperature of a particular area of the filament is then known to a high degree of accuracy. However, it must be remembered that the NBS calibration includes errors in the secondary standard pyrometer used at the National Bureau of Standards for calibration of the lamp. These uncertainties in lamp calibration are normally estimated by NBS to be comparable to the uncertainties in calibration of a tertiary standard pyrometer calibrated by NBS. Thus, the working standards available to a pyrometer manufacturer, from NBS, whether lamp or pyrometer, are comparable in uncertainty.

The promise of better calibration certainty by the standard lamp method under development is, therefore, in the area of reducing additional errors introduced in production calibration. This is expected to be affected by two important factors:

1. In routine calibration, the errors introduced in visual matching in a manual pyrometer will be reduced by use of a calibrated automatic electronic pyrometer (standardized Pyro-650).

2. Drift in either the lamp or the standardized electronic pyrometer will be checked periodically against the melting point of gold (1063°C).

In production operation it is not feasible to use an NBS calibrated lamp as the production reference, as the continuous service use of the lamp would cause excessive calibration drift in relatively few working days. To solve this problem, three NBS calibrated lamps will be used. One of these lamps will become the IDL master standard and will be used only to check from time to time the slow drift of the other two lamps, which will be secondary standards for calibration of the reference Pyro-650 units used in production calibration. Thus, the IDL master standard will see only a few hours' service but nowhere near what would be required for full production use.

Current will be measured at IDL when using the standardized lamps with highly precise equipment referenced to NBS calibrated electrical standardization equipment in the IDL Standards Laboratory.

The standard lamp functional pattern to calibrate the reference standard Pyro-650 is shown in Fig. 5.

To verify further the calibration of the reference standard Pyro-650 and particularly to check for slow drift of either the secondary standard lamps or the pyrometer, the calibration of the Pyro-650 at 1063°C can be checked by the melting point of gold by the setup shown in Fig. 6. Pyro-650 is focused on a pure gold foil target at the base of a blackbody cavity.[7] The muffle furnace is brought to a temperature slightly below the gold point, and then the vernier heater on the blackbody is used to slowly increase the temperature of the blackbody unit and the foil. Pyro-650 is continuously monitoring (and recording, if desired) the optical temperature of the gold foil until the instant it melts, at which time the circuit through the foil is broken and an alarm is sounded (or record marked) to indicate the instant of melting. The temperature is then assumed to be 1063°C.

The procedures described to this point in the standard lamp method effectively provide a calibrated automatic electronic pyrometer (Pyro-650) for use in the calibration system of Fig. 1 in place of the tertiary standard manual pyrometer. It is expected that use of the automatic electronic unit will both speed up calibration and, by eliminating the operator error in use of the manual standard, end up with slightly reduced over-all uncertainties.

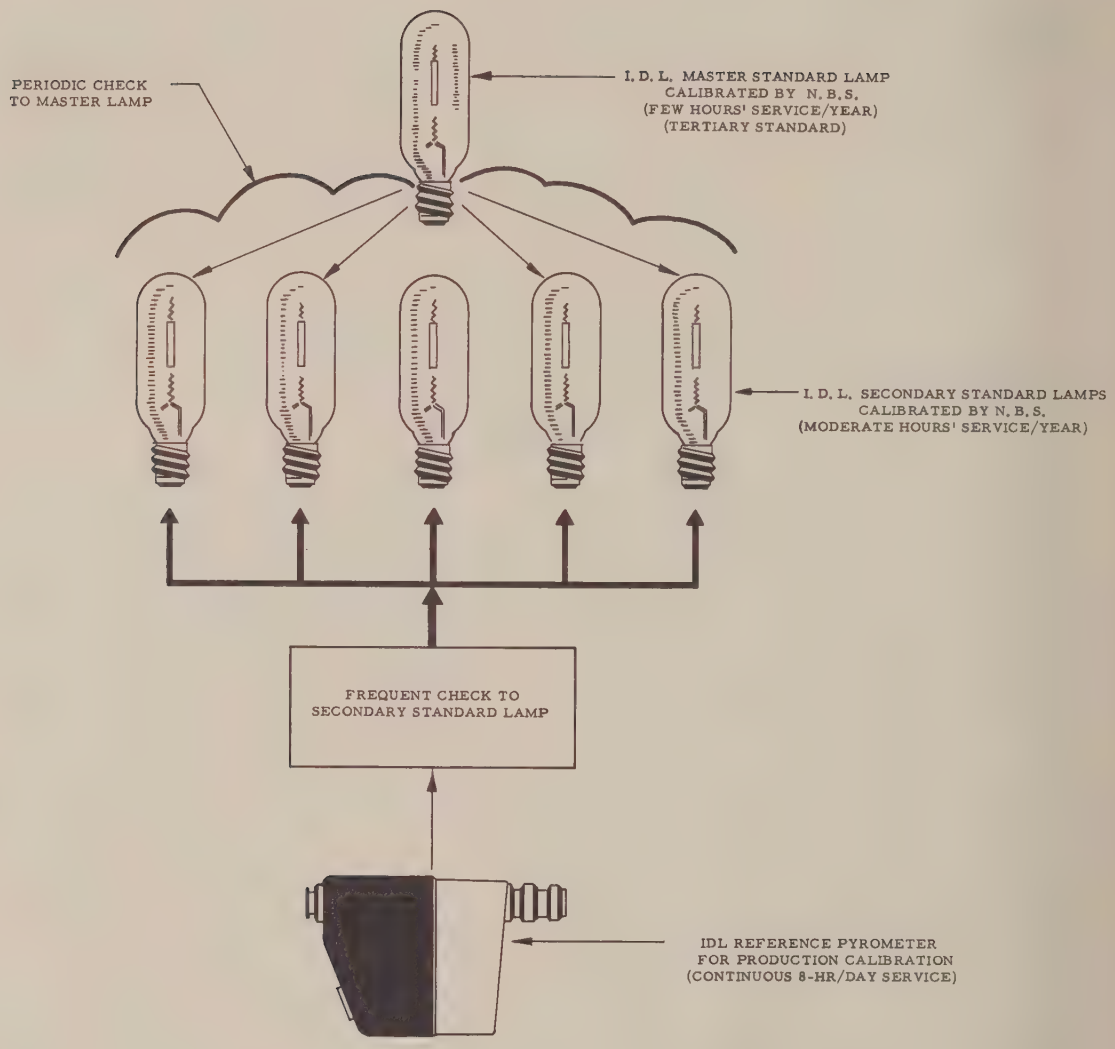
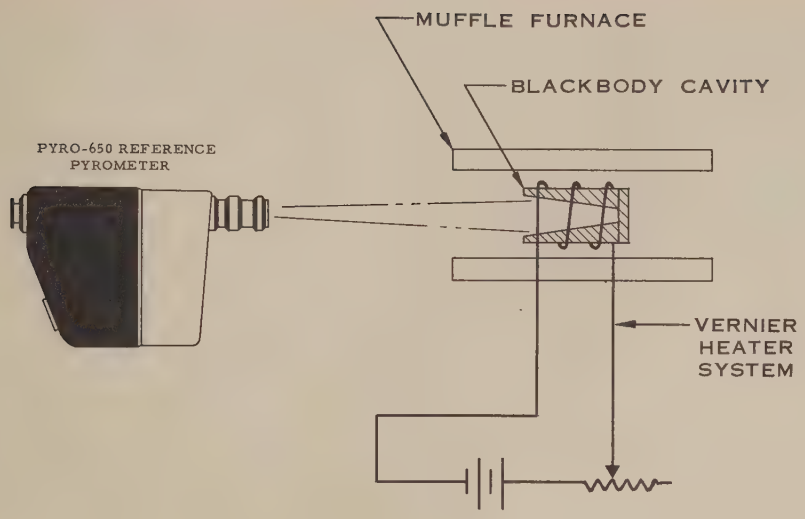


FIG. 5
SCHEMATIC OF STANDARD LAMP CALIBRATION SCHEME

a) GENERAL SCHEMATIC



b) ENLARGED DETAIL

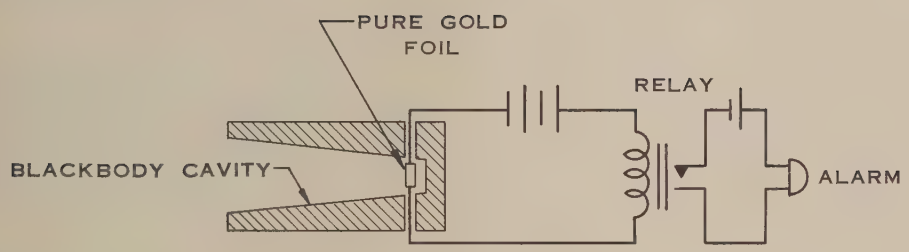


FIG. 6
SYSTEM USED TO CHECK GOLD POINT 1063°C
(PRIMARY STANDARD)

CALIBRATION OF PYRO-650 ABOVE 2300° C

General

Above 2300°C, calibration of Pyro-650 is made to conform to the International Temperature Scale of 1948 by procedures defined in the establishment of that scale, namely, extension by optical pyrometry on the basis of Planck's equation. The constant C_2 used is 1.4385×10^7, and the effective wavelength is 653 mμ.

It is important to understand that calibration by this method is the procedure defined by the International Temperature Scale above 1063°C and that the use of physical sources above 1063°C is merely a convenience when such sources are available and of sufficient accuracy of calibration to be used as reference standards. To date only the tungsten strip lamp qualifies as a suitable source for use to 2300°C. The zirconium arc, the carbon arc, and the sun are occasionally used as check points at approximately 2800°C, 3800°C, and 5750°C respectively. These are not primary standards of reference, however, as they are not sufficiently stable on an absolute basis. The sun's apparent temperature depends on atmospheric conditions and can vary widely with the particular area viewed.

Theory of Pyro-650 Operation

To understand the calibration of Pyro-650 above 2300°C, it is necessary to understand the operational principles of Pyro-650.

In simplified form, the optics of Pyro-650 are shown in Fig. 7. Energy from the source and from the stable internal reference lamp is alternately directed to the photomultiplier sensor by the flicker system. Only energy in a narrow band centered at 653mμ is permitted to reach the photomultiplier by the 653mμ interference filter.

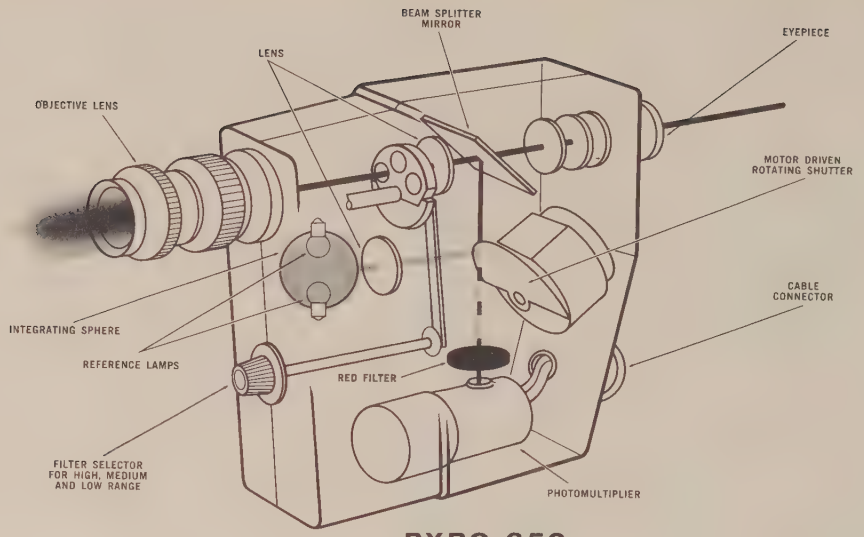


FIGURE 7

If the energy level from the source is exactly equal to that from the reference lamp J_O, then the energy reaching the phototube will not vary as the flicker system rotates, and no alternating current signal will be generated. By suitable electronic circuitry this no-signal condition corresponds to the Pyro-650 meter reading at mid-scale position (actually 50 μa which is a few degrees to the right of exact mid-scale due to detailed meter construction).

If the energy from the source is less or greater than J_O, an alternating current of magnitude proportional to the energy difference, and of phase reflecting lesser or greater level than J_O, will be generated at the multiplier. By suitable phase-sensitive rectifier circuits, a resulting dc current tends to drive the Pyro-650 meter up or down scale from the 50 μa mid-scale position. The amount the meter moves for a given energy level change is determined by the gain of the Pyro-650 amplifier, which may be set to a desired value during calibration and will remain highly stable at the selected setting. (Fig. 8.)

It will thus be seen that the meter scale is really a scale of relative energy levels from the source (at 653 mμ) compared to the reference energy J_O. If the energy from the source J_S is less than J_O (temperature lower), the ratio $J_S/J_O < 1$, and the meter moves to left of center (down scale). If J_S is greater than J_O (temperature higher), then $J_S/J_O > 1$, and the meter moves to right of center (up scale). The meter movement covers 0 to 100 μa dc.

Calibration Procedures (8)

To illustrate the calibration procedures, the scales of a model C301 instrument will be used (Fig. 9). This is a convenient scale for the purpose, for the following reasons:

1. The 1400°-2100°C scale is entirely within the range of tungsten lamp calibration.
2. The 1900°-2700°C scale is partially within the tungsten range and partially beyond.

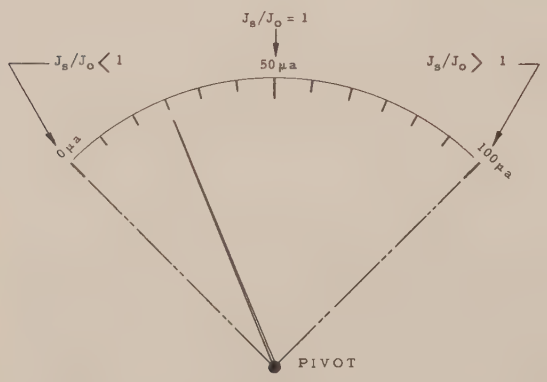


FIG. 8

METER SCHEMATIC DIAGRAM

FIGURE 9

3. The 2500°-3500°C scale is entirely above 2300°C and therefore outside the tungsten range.

To calibrate the lower scale, the techniques used in the previous section are functionally[9] used as follows:

1. Lamp temperature is set to approximate the mid-scale meter position (1680°C) and precisely measured with the NBS calibrated pyrometer. Bias adjustment on the meter has previously been set to give a mid-scale reading at the point of no ac signal from the photube.

2. A combination of neutral density filter and diaphragm stop is introduced into the source beam within the instrument to attenuate the source energy. The attenuation is adjusted until the meter reads 1680°C (or the precise measured temperature) within calibration tolerance. This operation is effectively balancing energy from the source and the reference lamp at the mid-scale temperature of 1680°C.

3. Next, the source temperature is set to approximately 1400°C and the exact temperature determined by the NBS calibrated pyrometer. Now the gain of the amplifier (labeled SPAN on the panel) is adjusted until the meter reads the correct temperature near 1400°C within calibration tolerance.

4. The procedure can be repeated at the 2100°C end for verification. If the scale has been correctly computed, the 2100°C graduation will automatically correspond to the J_1/J_0 ratio of 2100°C, and no further adjustment will be required.

In practice, the procedures (1) through (4) are repeated several times to get the best balance of readings and average out residual errors.

Now, proceeding to the mid-range scale 1900-2700°C, the center scale temperature of 2230°C is within the tungsten upper limit. Thus, the methods of (1), (2), and (3) above can be used to calibrate the mid-point and the low scale reading of 1900°C. This establishes the energy balance at 2230°C and the change in energy required to go from 50 μa mid-scale to 0 μa at 1900°C. The gain of the amplifier is now known, so the energy change required to reach 100 μa is a matter of simple arithmetic. This energy is found to correspond to 2700°C and the 100 μa meter point is so labeled. (In actuality, during scale layout, the lower and upper limits corresponding to 0 and 100 μa are selected arbitrarily. The corresponding energy levels define the required amplifier gain, and therefore the energy and corresponding temperature at mid-scale. Intermediate graduations are determined on an energy basis, but labeled in temperature units.)

Thus, on the mid-range scale, the balance point at mid-scale and the gain of the amplifier on the down-scale motion have been established by comparison to a tungsten source. Up-scale calibration is then a mathematical computation based on Planck's law. However, the following important features of this approach should be noted:

1. The complete lower scale 1400-2100°C can be calibrated against the NBS pyrometer to determine accuracy throughout the scale, therby checking over-all performance of the energy-measuring optical electronic system.

2. When the additional filter is introduced into the source beam for mid-range, mid-scale calibration at 2230°C, the energy reaching the multiplier is exactly the same as for 1680°C on the lower scale. Thus, the optical-electronic energy comparison becomes identical to that of the lowest scale, except for a change in amplifier gain setting, if the energy ratios to the selected mid-range scale limits are not identical to those of the low range scale. This means that the Pyro-650 optical electronic system is measuring energy of the same levels and with the same errors as exhibited on the lowest scale. The change in gain required for each scale does not noticeably affect the scale errors, due to the very stable electronic circuitry.

Next, consider the high range scale. It has been noted above that at the mid-point of each scale (1680° and 2230°C) energy from the source balances energy from the reference lamp. What were the energy ratio levels at these mid-points? For 1680°C (Table II), J_T/J_{Au} = 182.91. For 2230°C, J_T/J_{Au} = 2180.

The mid-point of the high range scale is 2910°C (Fig. 10). For this temperature, J_T/J_{Au} = 14,300.

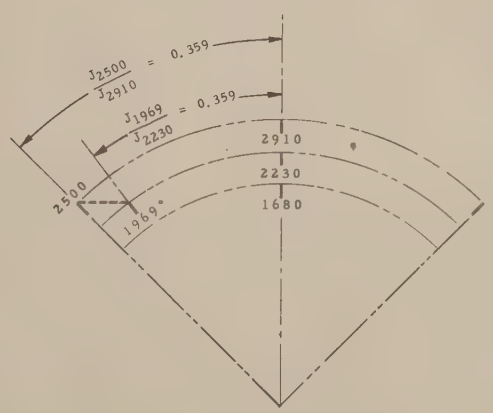


FIG. 10

GAIN SETTING FOR UPPER SCALE

Now, the internal filter-plus-diaphragm stop energy attenuator in Pyro-650 was adjusted on mid-range scale until there was an energy balance at 2230°C (mid-scale) for an energy level JT/J_{Au} of 2180. To read at the same meter deflection when looking at a temperature of 2910°C, an additional attenuator must be introduced on the high-scale filter position to reduce the energy ratio JT/J_{Au} of 14,300 at 2910°C to 2180. The filter must, therefore, have a transmission of 2180/14300 = 0.1524, or 15.24%.

Therefore, an additional filter of 15.24% (with suitable tolerance) inserted in the beam will automatically introduce the International Temperature Scale of 1948 by employing Planck's equation for calibration at the mid-point 2910°C without reference to an actual source at that temperature. The filter transmission can be checked in either of two ways: one is to measure the transmission on a spectrophotometer; the second is to check it on a lower scale range by the following procedure:

1. Set a tungsten lamp to read, say 1700°C against a calibrated optical pyrometer. At this temperature $J_T/J_{Au} = 204.86$.

2. Introduce the filter under test. If it has an effective transmission of 15.24% the pyrometer will see an energy level $J_T/J_{Au} = 0.1524 \times 204.86$, or 31.22. This corresponds to a temperature of 1435°C. Thus, if the pyrometer reads 1435°C with the test filter in place, it verifies the transmission as 15.24% within test error. Obviously, if the reading is other than 1435°C, the energy level tables or Planck's equation can be used to compute the exact effective filter attenuation.

So far only the mid-point of the high range scale has been calibrated. To complete the task, the amplifier gain must be adjusted to give the desired meter deflection from mid-point for the energy ratio changes corresponding to the scale markings.

To check this, first consider what energy ratio change is necessary to go from mid-point 2910°C to the left end graduation of 2500°C on the high scale. This ratio is:

$$\frac{J_T/J_{Au} \text{ for } 2500°C}{J_T/J_{Au} \text{ for } 2910°C} = \frac{5{,}140}{14{,}300} = 0.359$$

Since the absolute energy levels seen at mid-point by the internal optical-electronic system are identical on each scale, the gain can be set for the high scale by adapting the known desired energy reduction ratio to measurement within the limits of a tungsten source. To do this, assume the additional filter used on the high scale is removed, but the electronics remain in high scale position. The high scale will now read 2910°C when the pyrometer is focused on a tungsten filament operating at a brightness temperature of 2230°C, as the pyrometer will actually be operating on the mid-range scale. The energy level for 2230 is $J_T/J_{Au} = 2180$. To set the gain for high scale calibration now, it is desired that the meter move to the 2500°C scale point when the energy of 2180 is reduced by the ratio 5140/14300 corresponding to a temperature change of 2910°C to 2500°C. This represents a net energy ratio of 2180 x 5140/14300 = 783, or an actual brightness temperature of 1969°C.

Thus, if the tungsten lamp is set to 1969°C brightness temperature and the amplifier gain adjusted until the meter reads 2500°C, the gain for the high range scale will have been set to conform to Planck's equation. Note that the reference lamp must be set to 1969°C by an external standard pyrometer; even though the Pyro-650 is operating optically on the mid-range scale, the electronics are operating on high range, so the meter will read 2500°C high range, not 1969°C mid-range.

As soon as the 15.24% additional attenuator filter is replaced in the internal filter selector wheel in the high range position, the high scale range is operable and calibrated.

Obviously, the principles described above can be applied to verifying as many scale points as desired. The principles can also be applied to even higher temperature scales, as Planck's equation combined with optical pyrometry is theoretically the definition of the International Temperature Scale indefinitely upwards from 1063°C. The uncertainties of calibration will increase somewhat as temperatures increase.

At higher ranges the net filter attenuation becomes quite great, and accuracy of measurement of filter transmission is a problem. To improve this condition, filters are used in series. Thus, two 10% filters in series give an effective attenuation of 1%, but since each 10% filter can be more precisely measured than a 1% filter, the attenuation of two 10% units in series is known much more accurately than that of a single 1% filter.

Summary

Calibration of Pyro-650 above 2300°C is accomplished by methods employing Planck's equation extrapolation of the International Temperature Scale of 1948 above the primary fixed gold point of 1063°C. The methods used conform to the definition of the International Temperature Scale above 1063°C and can theoretically be extended upwards in temperature indefinitely for a blackbody radiator.

CALIBRATION PROCEDURES FOR PYRO-EYE TWO-COLOR PYROMETER

General

The basic method of measurement of temperature by optical means is the brightness method. This is the definition of temperatures above 1063°C and is the normally accepted method of optical pyrometry for temperatures somewhat lower than 1063°C, possibly down to 650-700°C.

As high temperature processes have developed, there have evolved certain applications where the two-color method of optical pyrometry has certain advantages. Consideration of the relative merits of brightness versus two-color pyrometry is covered in several technical papers, some of which are included in the list of references at the end of this paper.

Since there are applications for both types of instrument, IDL offers the PYRO-EYE two-color automatic electronic pyrometer in addition to the PYRO-650 automatic electronic brightness pyrometer.

Calibration techniques for Pyro-Eye are similar in principle to those of Pyro-650, and the equipment used is identical. However, color temperature is not so clearly defined by international agreement as is brightness temperature, so some discussion is included here to assist in understanding the theory behind calibration of two-color instruments.

Definition of Color Temperature

Perhaps the best definition of color temperature in a physical sense is the apparent color to an observer of a blackbody radiator operating at a certain true temperature (by the International Temperature Scale). This is the sense in which color temperature is used in photography and is an indicator of the apparent color to an observer of the source of illumination. For example, average daylight has a color temperature of about 6500°K. It can be duplicated reasonably well by a tungsten lamp operating at a brightness temperature of some 2400°C plus a bluish filter. The light from such a source and filter, falling on a white surface, can have a color temperature of 6500°K, but the surface itself may be at room temperature.

In pyrometry, color temperature is used as a measure of temperature of the source. The degree to which color defines the source temperature is dependent on many factors, and to have color accurately define temperature, the exact spectral radiation characteristics of the incandescent body must be known. For practical work, however, and for standardization of methods of instrument calibration, the spectral radiation pattern of a blackbody operating at a temperature T is assumed standard for temperature T.

Radiation from a blackbody as a function of temperature and wavelength was seen to be governed by definition above 1063°C by Planck's law. The radiation energy from Planck's law is plotted for various temperatures in Fig. 11.

Two-Color Pyrometer Operation

The optical system of the Pyro-Eye two-color pyrometer is shown in Fig. 12. The photoelectric and optical system alternately views the target through two narrow band filters, one peaking at 470mμ and the other at 640mμ.[10]

The instrumental measurement made is a ratio of energy at 470 mμ to energy at 640mμ. This energy ratio is directly a function of apparent blackbody temperature.

Planck's law states that this energy ratio will be:

$$\left(\frac{J_{470}}{J_{640}}\right)_T = \left[\frac{.470}{.640}\right]^{-5} \times \left[\frac{e^{\frac{C_2}{(T+273)(.640)}} - 1}{e^{\frac{C_2}{(T+273)(.470)}} - 1}\right]$$

where C_2 = Planck's constant (1948 value) = 1.4385 x 10^7.

Table V gives typical values of this energy ratio as a function of color temperature.

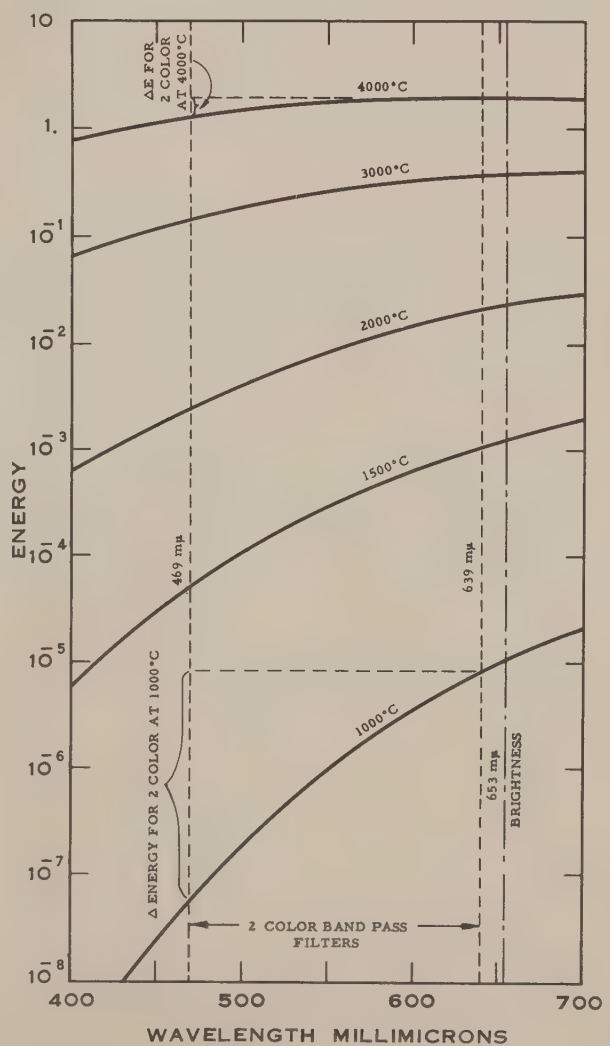


FIGURE 11

SCHEMATIC DIAGRAM SHOWING OPTICAL ARRANGEMENT OF PYRO-EYE

FIGURE 12

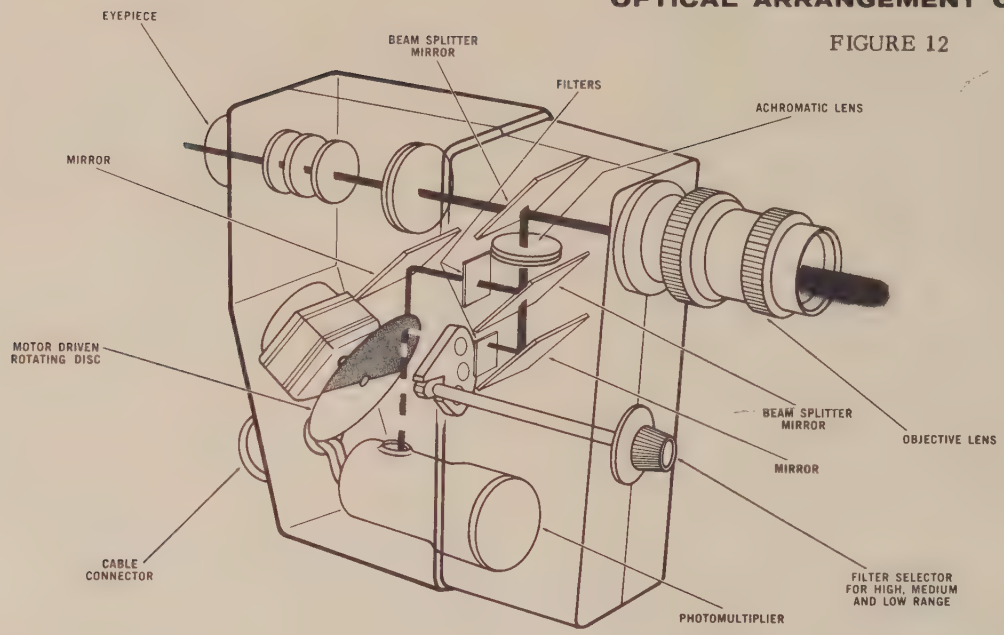


Table V. Energy Ratios, 470mμ to 640mμ, for Apparent Color Temperature, Blackbody Radiation

Color Temp. T, °C	Energy Ratio $\frac{J_{470}}{J_{640}}$ T	Color Temp. T, °C	Energy Ratio $\frac{J_{470}}{J_{640}}$ T
800	1738	2050	31.34
850	1240	2100	29.12
900	916.4	2150	27.17
950	693.1	2200	25.40
1000	556.6	2250	23.81
1050	423.0	2300	22.40
1100	339.3	2350	21.12
1150	276.6	2400	19.95
1200	228.5	2450	18.90
1259	191.1	2500	17.87
1300	161.7	2550	17.02
1350	138.3	2600	16.16
1400	119.3	2650	15.43
1450	103.9	2700	14.77
1500	91.05	2750	14.11
1550	80.57	2800	13.54
1600	71.61	2850	13.00
1650	64.05	2900	12.41
1700	57.69	2950	11.98
1750	52.12	3000	11.57
1800	47.41		
1850	43.29		
1900	39.73		
1950	36.57		
2000	33.73		

In a simplified example, as the energy from the source reaches the photomultiplier, if the effective energies at 470 mμ and 640 mμ are equal, no output signal would be generated. The effective energies reaching the tube and generating electrical signals are actually the source energies at the two wavelengths as modified by, the filter attenuation in each path and phototube spectral sensitivity. If the source is set at some fixed temperature within sensing range of the instrument, it is obviously possible to insert attenuating filters in one beam or another to obtain zero signal output for that temperature. Thus, in calibrating, a temperature for zero output signal can be selected as desired. Once this temperature is selected, the ratio J_{470}/J_{640} for the source for this nulled output point is known from Planck's equation.

Calibration Procedure - Pyro - Eye

Consider the simplest case of calibration of a Pyro-Eye scale (Fig. 13). At some temperature T_o, the proper amount of attenuation is introduced into one beam or other to obtain zero signal output when looking at a source of color temperature T_o. Then the 0 μa meter graduation corresponds to temperature T_o.

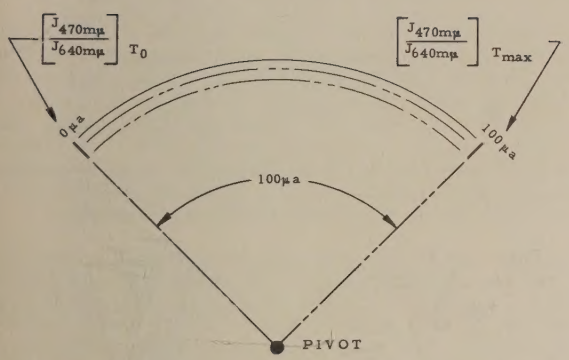


FIG. 13

SIMPLE SCALE CALIBRATION FOR PYRO-EYE

If now the instrument is focused on a target of temperature T_{max}, which is the desired full scale reading corresponding to a 100 μa meter reading, the gain of the electronics needs only to be adjusted until the meter reads full scale. This point is then labeled with temperature T_{max}. However, the following relation is known:

$$K\left[\frac{(J_{470}/J_{640})_{T_{max}}}{(J_{470}/J_{640})_{T_o}} - 1\right] = 100\,\mu a \quad *$$

Therefore, K can be determined and for any intermediate temperature T the corresponding μa can be computed as follows:

$$(\mu a)_T = K\left[\frac{(J_{470}/J_{640})_{T_{max}}}{(J_{470}/J_{640})_{T_o}} - 1\right]$$

The actual circuitry of Pyro-Eye is designed so that the instrument is always calibrated with a bias current which drives the meter below zero when the source energy is interrupted (which results in no signal output from the photosensitive system). This is a design feature to insure that recorder or control circuits will drive down scale if the viewing beam is interrupted.

Consider, therefore, the practical scale problem of Fig. 14. In designing the scale, a no-signal temperature T_o was selected for some particular depressed zero meter indication corresponding to a bias current I_B. Thus, if the instrument is balanced with no bias for T_o at 0 μa (Fig. 13), then bias current I_B is applied, the apparent scale point for T_o would be below the meter zero by I_B μa.

With I_B applied, the instrument may now be focused on a target of desired full scale temperature T_{max} (Fig. 14), and amplifier gain adjusted to read T_{max} at a meter current of 100 μa. The formulae used for graduating the scale for intermediate points then become:

$$K = \left[\frac{(J_{470}/J_{640})_{T_{max}}}{(J_{470}/J_{640})_{T_o}} - 1\right] = (100 - I_B)\,\mu a \quad **$$

*This equation is the operational equation of the pyrometer electronic circuitry.

**I_B is a negative value.

K is determined and intermediate graduations computed as:

$$(\text{Meter } \mu a)_T = K\left[\frac{(J_{470}/J_{640})T_{max}}{(J_{470}/J_{640})T_O} - 1\right] - I_B\,\mu a$$

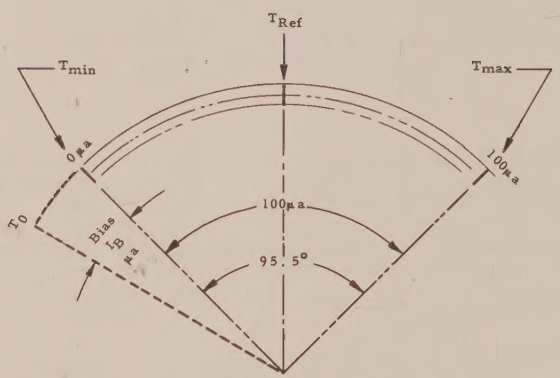


FIG. 14
GENERALIZED PYRO-EYE SCALE

The foregoing description has combined a discussion of calibration procedures and scale design to simplify understanding of Pyro-Eye operation. In practice, the scales are precomputed and manufactured by the energy ratio considerations described, and calibration is a matter of adjusting bias and gain to force the instrument to match the scale.

Where the entire scale is within tungsten lamp range, the procedure is substantially:

1. Select internal filters in the head to known T_O used in scale design (with bias removed).
2. Apply measured bias I_B per scale design.
3. Set gain by measurement at T_{max}.
4. Recheck readings at T_{min}. and several check points, making minor bias and gain adjustments to achieve best calibration.

Calibration above 2800° C

Above the limit of tungsten sources (2800°C color temperature), Planck's law relationships are used to calibrate Pyro-Eye. However, the procedures are not quite the same as used on Pyro-650 because no scale normally supplied with two-color instruments lies entirely outside a tungsten source limit. The highest normal two-color scale is 2300°-3500°C color temperature. The upper tungsten limit of 2800°C color temperature is, therefore, almost at mid-range.

This scale is computed from Planck's equation just as the other scales. In calibrating the points, T_O, T_{min} and T_{ref} are used (Fig. 14), where T_{ref} is the 2800°C upper tungsten limit. Above 2800°C to 3500°C the scale represents instrumentation of Planck's equation. To insure that this will be accurate, the amplifier gain may be checked by other electronic means if desired.

It is perfectly feasible to extend ranges even higher and use methods of measured attenuation similar to those employed in Pyro-650, but the two-color method inherits added uncertainties at temperatures much higher than 3500°C due to the reduction in differential signal ratios available for measuring purposes. Brightness methods are superior at higher temperatures in all except a very few cases of peculiar target and viewing conditions.

REFERENCES

(1) Much of the subject matter of this chapter is covered in detail in a paper by J.A. Hall, National Physical Laboratory, Teddington, England, "The International Temperature Scale." Reference: Wolfe, Hugh C. (Ed.), Temperature, Its Measurement and Control in Science and Industry, 2, Am. Inst. Phys., Reinhold Publishing Corporation, New York, 1960.

(2) Holborn, L., and Day, A., Ann. Physik, 2, 505-545 (1900).

(3) Day, A.L., and Sosman, R.B., "High Temperature Gas Thermometry," Carnegie Institute publication (1911).

(4) Birge, R.T., Repts. Progr. in Phys., 8, 90-134 (1941).

(5) DuMond, J.W., and Cohen E.R., Revs. Modern Phys., 25, 691-708, (1953).

(6) The NBS calibration to 2300°C is by the comparison to a tungsten strip filament lamp as illustrated. The 2400-2800°C range certification by NBS are extrapolated values.

(7) This method was described to IDL by AVCO engineers who have successfully developed the method for gold point check.

(8) The description given assumes use of the tertiary standard pyrometer method of calibration. Procedures for the standard lamp method are similar.

(9) This is a functional calibration description only to simplify the presentation. For any actual calibration, precise procedures must be followed. These are available on request to owners of Pyro-650 instruments. On the scale used for illustrative purposes the temperatures 1680, 2230, and 2910 are referred to as mid-scale points. Due to slight meter non-linearity, actual 50 μa points are a few degrees higher. For simplification of this presentation, this will be ignored.

(10) For instruments with scale temperatures below 1000°C, slightly different wavelengths and broader band-pass filters are used due to limited available energy at these low temperatures.

(11) The international conference of 1948 agreed to adopt the term "Celsuis" instead of Centigrade for the Int'l. Temp. Scale. For practical purposes they may be considered synonymous. For detailed information on Celsius, the paper of ref. (1) above should be consulted.

(12) In 1960 the Eleventh General Conference of Weights and Measures renamed the Int'l. Temp. Scale of 1948 the "International Practical Temperature Scale".

Other References of Interest:

Pyro-Eye Instruction Manual No. 5037; Inst. Dev. Labs., Inc., Attleboro, Mass. (1960).

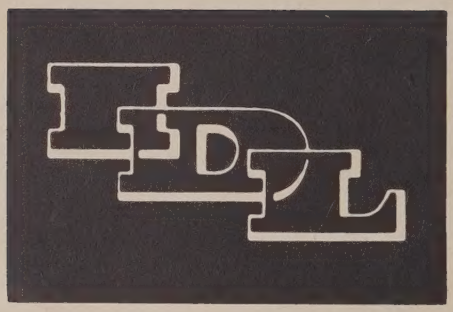
Pyro-650 Instruction Manual No. 5040; Inst. Dev. Labs., Inc., Attleboro, Mass. (1961).

Lee, R.D., "Calibration of Optical Pyrometers and Ribbon Filament Lamps at the National Bureau of Standards," paper.

Ackerman, S., "A Review of Automatic Radiometric Pyrometry," Temperature, Its Measurement and Control in Science and Industry (Reinhold Publishing Corp., New York, 1961), Vol. III.

Ackerman, S., "Notes on the Design and Performance Characteristics of a Two-Color Pyrometer," Temperature, Its Measurement and Control in Science and Industry (Reinhold Publishing Corp., New York, 1961), Vol. III.

Lord, J.S., "Design and Performance Characteristics of an Automatic Brightness Pyrometer," Temperature, Its Measurement and Control in Science and Industry (Reinhold Publishing Corp., New York, 1961), Vol. III.



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